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Investigation of material removal and surface topography formation in vibratory finishing

Eckart Uhlmann[a], Arne Dethlefs[a]*, Alexander Eulitz[a]

[a]Technical University Berlin, Institute for Machine Tools and Factory Management, Berlin, Germany

* Corresponding author. Tel.: +49-30-314-22413; fax: +49-30-314-25895. *E-mail address:* dethlefs@iwf.tu-berlin.de

Abstract

In this work investigations on vibratory finishing and an approach towards a process model combining the Discrete Element Method (DEM) with experimental results will be presented. Based on experimental data from vibratory finishing and drag finishing experiments, material removal is considered on a surface roughness level, leading to a new model for surface roughness prediction. The influence of several abrasive particles and process parameters on the surface topography formation was investigated using steel rods with different topographies. Core findings include differing material removal mechanisms depending on initial surface roughness and a first description of the influence of particle shape on surface topography formation. To develop a comprehensive process model for vibratory finishing, DEM is used to model the motion of the bulk of abrasive particles and its contacts with the workpiece. Given the results from the simulation such as number, intensity and location of contacts for a set of boundary conditions, such as workpiece speed and bowl excitation, experimental findings can be linked to these computable results.

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Keywords: Abrasive processes; Vibratory Finishing; Mechanics and dynamics of material removal processes; Simulation

1. Introduction

Vibratory Finishing is a widely used technology for surface roughness improvement and edge rounding, applying loose abrasive particles as tools. Nevertheless only few researchers have investigated this technology and findings are limited to results of empirical studies of specific applications [1, 2]. Proposed process models so far predict material removal over time or discuss the steady state period of surface topography formation [2, 3]. Great relevance lies in a comprehensive process model for vibratory finishing or mass finishing in general that can predict surface roughness considering the kinematics of the process and the mechanisms of surface topography formation.

Nomenclature

t_P	processing time
f_a	excitation frequency
v_W	workpiece speed
Rz_i	initial surface roughness
Rz	surface roughness
d_N	workpiece diameter
F_n	normal force
F_t	tangential force
E	Young's modulus
ν	Poisson's ratio
ρ	density
μ	friction coefficient
dmp	global damping constant

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2. Scientific approach

The results presented in this paper were achieved as part of a project which aims to develop a comprehensive process model for mass finishing that combines findings about process fundamentals and basic material removal mechanisms with an empirical process model that can be used to predict surface formation for given parameters and a model to numerically simulate contacts between abrasive media and workpieces using the Discrete Element Method (DEM). Fig. 1 illustrates the overall approach in this project.

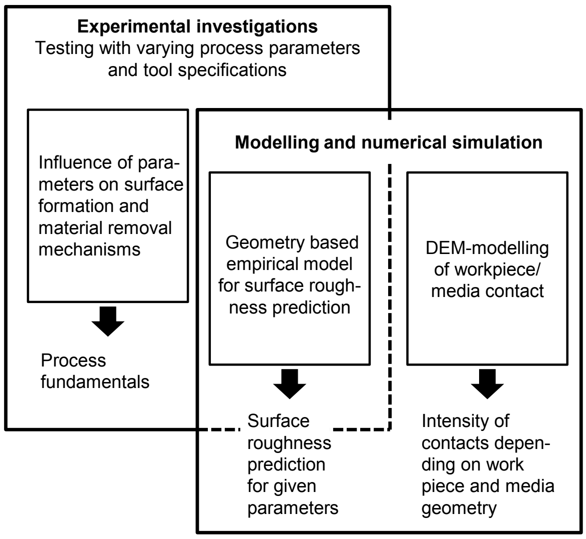

Fig. 1. Approach for a comprehensive process model for mass finishing

The investigation of the material removal mechanisms aims to provide answers to the question how surface formation is influenced by different processes like vibratory and drag finishing, process parameters such as processing time t_P, excitation frequency f_a and workpiece speed v_W, commercially available abrasive media and the initial surface roughness Rz_i of workpieces. Furthermore, experimental results are utilized in an empirical model describing material removal at a surface roughness level. With this model, surface roughness can be predicted for a given set of parameters. The comprehensive process model for mass finishing is completed with a model for particle contact using DEM. The goal is to simulate the number, type and intensity of contacts between workpieces and abrasive media for finite areas of any workpiece. By using the DEM-model to simulate the processes investigated in the experiments, a link between contact intensity and surface roughness formation can be established. Findings on process fundamentals are utilized to broaden applicability of the model and ensure transferability.

3. Experimental procedures

All experimental investigations were carried out using a vibratory finishing bowl Rösler R220DL in combination with a 6-axis robot Comau NJ 370, Fig. 2. The full factorial experimental design combines the processes drag finishing, vibratory finishing with fixed parts and combined vibratory and drag finishing. Experimental parameters are shown in Table 1. Note that the combination of $f_a = 0$ Hz and $v_W = 0$ m/min was not considered.

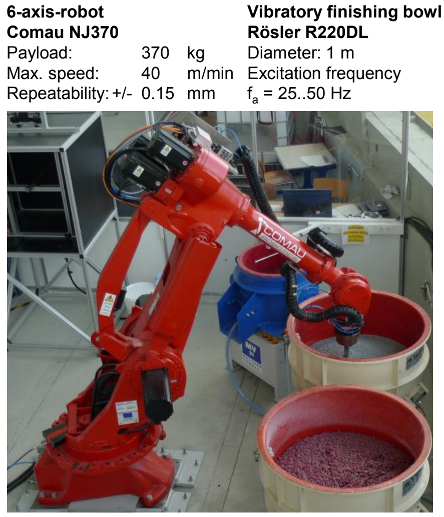

Fig. 2. Experimental setup for the technological investigations

Table 1. Parameters for the technological investigations

Parameter	Values
Mean initial surface roughness Rz_i	7.9; 15.7; 26.7 µm (fine, medium, coarse)
Bowl excitation frequency f_a	0; 30; 50 Hz
Workpiece speed v_W	0; 10; 30 m/min
Process time t_P	1; 3; 5; 15; 30 min
Abrasive media	Walther Trowal FSG 6 BALL
	Walther Trowal FSG 10x10 TRI

The two commercially available ceramic abrasive media used differ in size and shape - one is spherical with 6 mm in diameter and one is a cylinder of 10 mm height and 10 mm equilateral triangular cross-section, Fig. 3. Both media are Walther Trowal FSG-quality; according to the supplier they have the same fundamental abrasiveness.

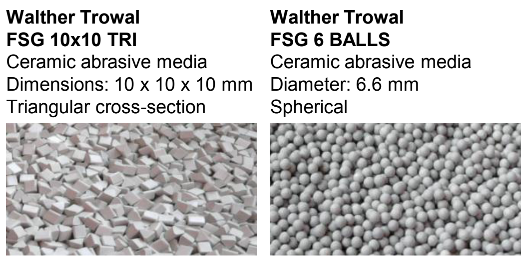

Fig. 3. Abrasive media for the technological investigations

In the intervals described by the process time t_P, Table 1, surface roughness measurements were carried out with a Mitutoyo Surftest SJ-210 tactile profilometer. A measurement system analysis yielded a coefficient of variation of COV = 0,9 % when measuring surface roughness Rz thus being accurate enough to document the results of the investigation.

Workpieces used for all tests were 1.4301 steel rods with a diameter of d_N = 40 mm and a length of 250 mm. The part of the steel rod that is dipped into the media is machined by turning leading to three different initial surface roughness profiles Rz_i. The coefficient of variation for the initial surface roughness Rz_i after turning is COV = 7 %.

4. Experimental findings

Fig. 4 exemplarily shows the development of the surface roughness Rz over the process time t_P for an excitation frequency of f_a = 50 Hz and a workpiece speed of v_W = 30 m/min. The difference between the two abrasive media used is apparent. Generally a tendency towards a faster improvement of the surface roughness Rz in the beginning of the process can be observed. Furthermore it becomes clear, that after t_P = 30 min of processing the threshold roughness as proposed by [3] is not yet reached. This is true for all experiments described here, thus the results presented here all deal with the industrially important transient period of mass finishing in which material removal is not constant and surface roughness improvements can be observed [3].

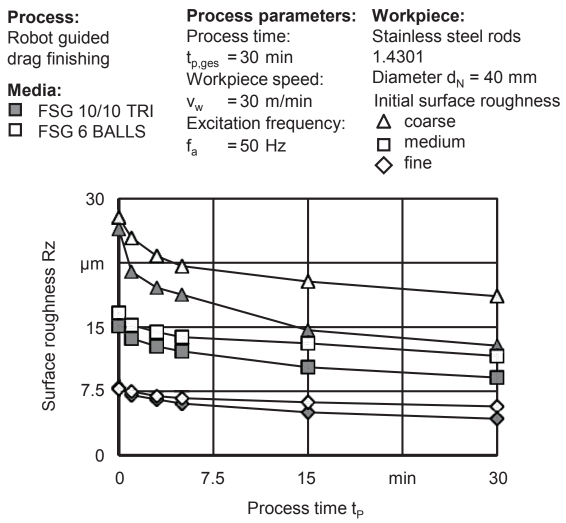

Fig. 4. Development of the surface roughness Rz over process time t_P

Considering the percentage decrease in surface roughness Rz relative to the initial surface roughness Rz_i as shown in Fig. 5, a particular effect can be seen, that was generally observed in all experiments. The percentage decrease in surface roughness Rz for a given set of parameters does not linearly depend on the initial surface roughness of the workpiece. The shape and size of the abrasive media used seem to be of higher importance.

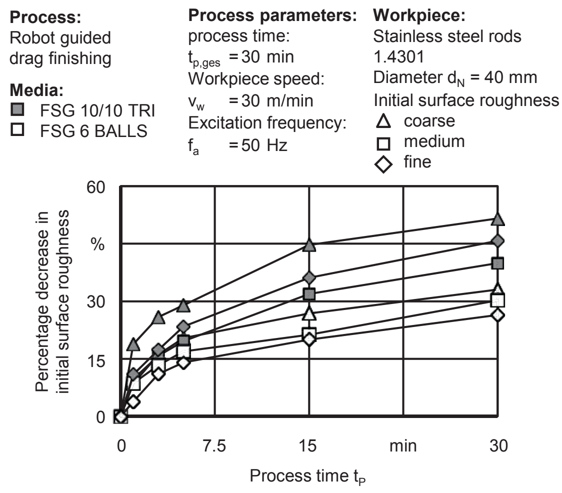

Fig. 5. Percentage decrease in surface roughness Rz relative to the initial surface roughness Rz_i

Given the aforementioned findings and considering the mass removal during these experiments, an interesting result can be seen. All initial surfaces have periodic roughness profiles that can, considering the cross-section, roughly be modeled as triangles as shown in Fig. 6. Here two idealized profiles are shown, the grey line represents a coarse initial profile, the dotted line a fine initial profile of half the profile height, grey areas represent removed material. Assuming, that after a certain process time, both profile heights have decreased by roughly 50 %, as observed in most experiments, Fig. 6 illustrates well, that the material removal rate is twice as high for an initial surface roughness of twice the amount. This means, that for a given abrasive media and set of process parameters the material removal rate is not constant in the transient process period but roughly linearly dependent on the initial surface roughness. In the investigations described here, the material removal rates for the coarse initial surface roughness were 1.5 to 2 times higher than for the fine initial surface roughness, depending on the process parameters.

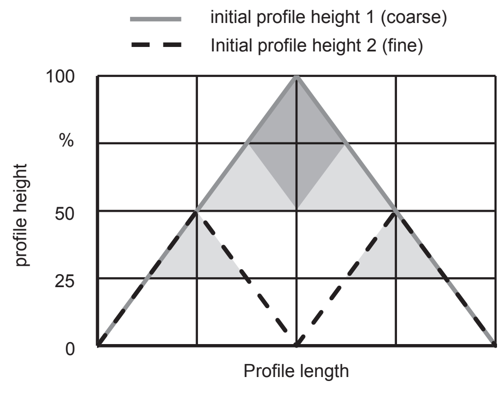

Fig. 6. Conceptual approach to explain material removal in mass finishing processes

The setup of the experimental investigations presented in this paper enables an investigation of the influence of the shape and size of abrasive media on the surface roughness formation. At an average the performance in terms of surface roughness improvement of the spherical media is 34 % lower in comparison to the triangular media. As the two media are composed of the same abrasives, this difference has to be ascribed to the shape and size of the particles.

It is generally accepted, that abrasive media with sharp edges have a higher impact on the surface roughness [4], resulting in higher material removal rates. In further tests carried out in the aforementioned project, abrasive particles with a star-shaped cross-section were tested against the spherical and triangular media. These tests strongly supported this theory and showed that mainly the contact of the edges of the abrasive particles with the surface of the workpiece leads to a material removal. For the two abrasive particles tested here, the triangular particle has a much lower edge radius than the spherical particle. In theory this will enable the triangular particle to reach deeper into the profile of the surface roughness, especially during the first minutes of processing, when the asperities of the roughness profiles are flattened. This removal mechanism can be described as more cutting-like. After removal of the asperities, this difference should level out and the material removal mechanism should become more abrasion- or micro-cutting-like. Two distinct phases of surface formation can be observed during the total process time of $t_P = 30$ min when looking at Fig. 5 and Fig. 6. A steep incline of the curve can be observed roughly during the first five minutes of processing followed by a much smaller incline. To investigate this, the rate with which the surface roughness improves per time unit - the slope of the curves in Fig. 5 and 6 - was considered for vibratory finishing ($f_a = 50$ Hz; $v_W = 0$ m/min) and drag finishing ($f_a = 0$ Hz; $v_W = 30$ m/min), Fig. 7.

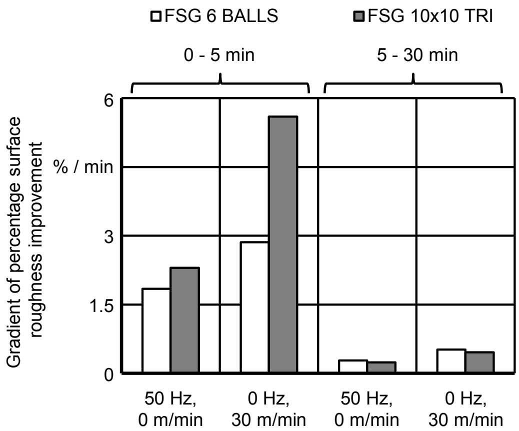

Fig. 7. Gradient of percentage surface roughness improvement per time unit in vibratory and drag finishing

Obviously vibratory and drag finishing show a different behavior. The advantage in improving surface roughness of the triangular media only becomes fully apparent in drag finishing. This can be ascribed to the higher forces acting in contact during drag finishing, especially with high speeds such as $v_W = 30$ m/min. Nevertheless the theory that media with sharp edges have an advantage when removing asperities in the first few minutes of the vibratory finishing process seems valid. The other tested parameter combinations show a similar behavior.

An overall view on the results from the presented technological investigation for the coarse initial surface roughness is given in Fig. 8. Shown is the percentage decrease in surface roughness Rz relative to the initial surface roughness Rz_i for both abrasive media after the total processing time of $t_P = 30$ min.

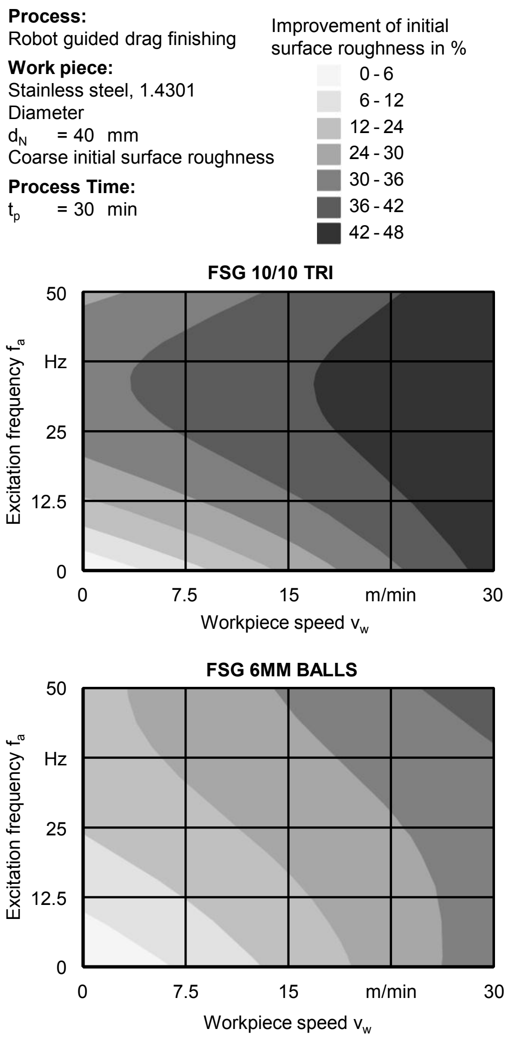

Fig. 8. Results from the experimental investigations for the coarse initial surface roughness

The results in Fig. 8 show a steady increase in surface roughness improvement for the spherical media with a rise in energy input. A higher energy input into the systems is given for an increase in excitation frequency f_a and workpiece speed v_W. A stronger effect on the surface roughness improvement can be observed for the workpiece speed v_W. For the triangular media this correlation cannot be derived in the same manner. Due to its differences in shape and size, a negative effect of the interaction between workpiece speed v_W and excitation frequency f_a can be observed for the triangular media, i. e. at high excitation frequencies f_a, the surface roughness improvement tends to decrease. An explanation for this effect can be, that an increase in the excitation frequency f_a leads to lower loads on the workpiece, as the pseudo-viscosity of the bulk media, as described by [5], decreases. On the other hand the relative speed between media and workpiece should increase with higher excitation frequencies f_a due to the flow of the media that is superposed with the workpiece v_W when combining vibratory and drag finishing.

Apparently the overall load on the workpiece is important for the performance of the triangular media, whereas media flow or relative speed between workpiece and media is essential for material removal with the spherical media. In conclusion the assumption seems valid, that for a material removal mechanism that relies mostly on abrasion and micro-cutting, as assumed for the spherical media, the relative velocity between workpiece and media is the main factor governing the material removal rate. For a material removal mechanism that relies mostly on cutting, as assumed for the triangular media, the intensity of the impact of the media determines the material removal rate.

5. Material removal model

Based on the work presented in this paper and data from further experimental investigations an empirical material removal model is developed that considers material removal on a surface roughness level [6]. The new approach aims to describe mass finishing during the transient period in which surface roughness improvement is observed. A method is presented to predict the roughness change after a given process time. In contrast to past approaches concentrating on mass or diameter loss of the workpiece, the model is based on geometric changes of the roughness-profile during the transient period of mass finishing. The model can be used to estimate process times needed to achieve a desired roughness of a workpiece. The output of the material removal model will later be linked to the contact intensity that can be calculated with the DEM-model described below, thus creating the comprehensive process model.

6. Modelling of the bulk motion

Bulk motion is modeled using the open source framework Yade [7] which is focused on DEM. Media is considered as a bulk of discrete purely elastic particles. Boundary conditions, i. e. bowl and workpieces, are implemented as facets. In case of spherical media the only occurring contact type is point-contact which reduces the effort for collision detection and contact calculation considerably. Even for aspherical media solely point contact can be established by clumping multiple spheres together. In that case, each of these clumps represents one abrasive particle. To simulate the number, type and intensity of contacts for finite areas of any workpiece a suitable model for particle-particle and particle-facet contacts has to be chosen. In the presented approach contact forces between two bodies are calculated according to the non-linear elastic simplified Hertz-Mindlin contact force model. This constitutive law is based on Hertzian contact equations [8] in normal direction and the Mindlin no-slip approach [9] in tangential direction.

Energy of the particulate media in the system is dissipated through contact friction and global damping of the absolute velocities of particles. Force transmitted in tangential direction between two particles is limited by the Mohr-Coulomb friction law (plasticity criterion). The input parameters for the contact model are Young's modulus E_i, Poisson's ratio ν_i, density ρ_i and friction coefficients $\mu_{i,j}$ for all materials i and material combinations i, j (i, j $\in$ m, i $\neq$ j with number of materials m). The model will be verified in several tests consisting of single and multi-contact, quasi-static and dynamic scenarios in which forces, measured in experiments and calculated in simulations will be compared.

Tens of thousands of abrasive particles are used in usual mass finishing processes, which results in immense calculation times on current, widely available computer systems for setups modelled exactly according to these processes. For that reason a smaller bowl and rod is considered as a first step towards a proof of concept. Furthermore spherical media is considered avoiding the necessity of building clumps. Geometric boundary conditions of the modelled setup can be found in Fig. 9.

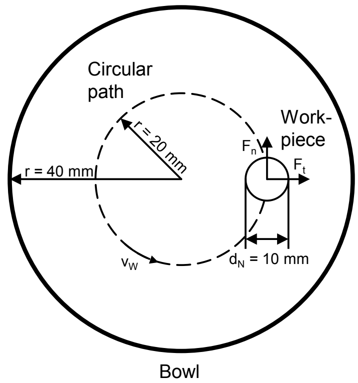

Fig. 9. Geometries of modeled small-scale process

In the simulation the total force acting on the rod is measured in a workpiece aligned coordinate system, i. e. normal force is always pointing in the direction of the workpiece velocity and the tangential force is perpendicular to it.

Fig. 10 shows the model setup and the total simulated forces in normal and tangential direction with spherical ceramic media and a steel rod for one revolution of the workpiece for a small scale process with geometries as described in Fig. 9. For simplicity bowl and rod are made of the same material. This reduces the number of occurring material combinations which results in less parameters that have to be determined experimentally beforehand.

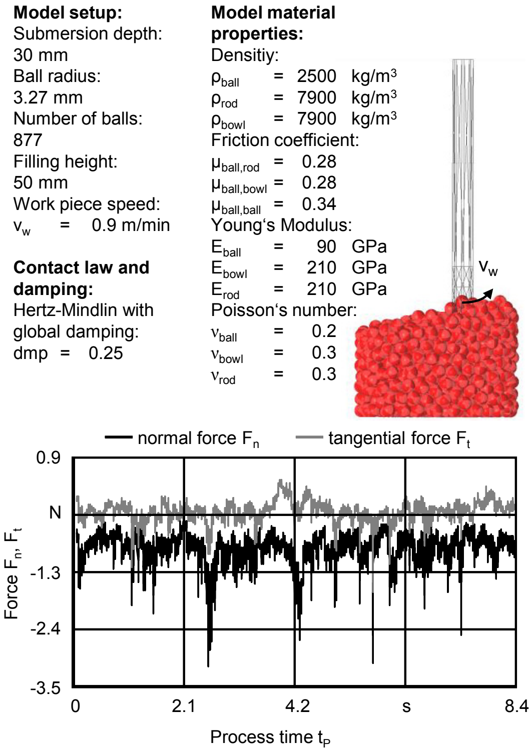

Fig. 10. Model setup and simulated forces for small-scale process

All necessary material parameters and the damping coefficient for this setup were determined in preliminary tests. As a next step workpiece and bowl described in Fig. 9 will be manufactured and the total force acting on the workpiece during a process similar to one modeled in Fig. 10 will be measured. Forces calculated in the simulation, see Fig. 10, show a considerable variation and some distinct peaks (minimal normal force is about $F_{n,min} = -3$ N). Force measurements in a real mass finishing bowl with spherical ceramic media show a similar behavior and comparable amplitudes. Obviously peaks of the normal and tangential force coincide. Consequently the resultant force points towards the center of the circular path and against the direction of workpiece movement. Most likely, this is related to certain contact events which will be examined in further research. The mean normal force is $F_{n,mean} = -0.775$ N whereas the mean tangential force is about $F_{t,mean} = -0.077$ N. Notably the normal forces are higher than tangential forces.

After the presented model is verified, it will be possible to determine the number, type and intensity of contacts between workpieces and abrasive media for finite areas of any workpiece.

7. Conclusion

An approach towards a comprehensive model for mass finishing is presented. The results from extensive experimental investigations provide a good data base for an empirical material removal model that considers material removal on a surface roughness level. Most importantly the analysis of the results from the experimental investigations has led to a deeper understanding of the material removal and surface topography formation in vibratory finishing. Core findings include:

- Material removal rates in the transient period of vibratory finishing are strongly dependent on the initial surface roughness, whereas the percentage decrease in surface roughness is similar for different initial surface roughness.
- Due to their more cutting-like material removal mechanism, media with edges have an advantage over round media when removing sharp asperities.
- The differences in improving surface roughness for round and edged media can mainly be observed in the first five minutes of processing.
- For a material removal mechanism that relies mostly on abrasion and micro-cutting, as assumed for spherical media, the relative velocity between workpiece and media is the main factor governing the material removal rate, whereas the intensity of the impact of the media seems to determine the material removal rate for a mostly cutting-like material removing mechanism, as assumed for the triangular media. In this case the intensity of the impact of the media determines the material removal rate.

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References

[1] Domblesky J, Cariapa V, Evans R. Investigation of vibratory bowl finishing. Int J Prod Res 2003;41:3943-3953.
[2] Cariapa V, Park H, Kim J, Cheng C, Evaristo, A. Development of a metal removal model using spherical ceramic media in a centrifugal disk mass finishing machine. Int J Adv Manuf Technol 2008;39:92-106.
[3] Hashimoto F: Modelling and Optimization of Vibratory Finishing Process. Annals CIRP 45 1996;45:303-306.
[4] Sangid MD, Stori JA, Ferriera PM. Process characterization of vibrostrengthening and application to fatigue enhancement of aluminum aerospace components - part II. Process visualization and modeling. Int J Adv Manuf Technol 2010;53:561 - 575.
[5] Cariapa V, Park H, Kim J, Cheng C, Evaristo A. Development of a metal removal model using spherical ceramic media in a centrifugal disk mass finishing machine. Int J Adv Manuf Technol 2008;39:92-106.
[6] Uhlmann E, Dethlefs A, Eulitz A. Investigation into a geometry based model for surface roughness prediction in vibratory finishing processes. 2013:Manuscript submitted for publication.
[7] Šmilauer V, Catalano E, Chareyre B, Dorofeenko S, Duriez J, Gladky A et al. Yade Reference Documentation. In: Šmilauer V, editor. Yade Documentation, The Yade Project, 1st ed.; 2010. http://yade-dem.org/doc/.
[8] Hertz H. Über die Berührung fester elastischer Körper. Journal für die reine und angewandte Mathematik 1882;92:156–171.
[9] Mindlin RD, Deresiewicz H. Elastic spheres in contact under varying oblique forces. J Appl Mech 1953;20:327-344